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## Adjustable-Speed Drives and Their Applications

As environmental and other concerns slow the growth of electrical energy generation in coming years, it becomes essential that we conserve and use limited and precious resources more efficiently. Conserving electricity and making it a better energy source relies on the widespread adoption of the power conversion process, which takes electricity from a source and converts it to a form exactly suited to the electrical load.

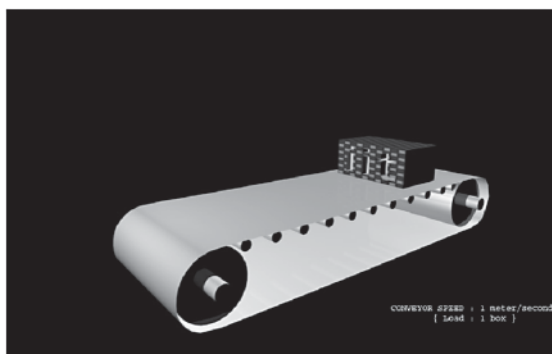
Electric motors consume more than 60% of all electrical power in the United States. Adjustable-speed drives (ASDs) can improve the efficiency of these motors by about 50% in many applications. They can also reduce costs considerably. Power electronics allows us to develop efficient speed and torque control of electric motors at low costs. This, in turn, calls for development of optimized electromechanical power conversion units.

Today's technology requires different speeds in many areas where electric machines are used. Electric machines that use traditional control methods have mainly two states—stop and

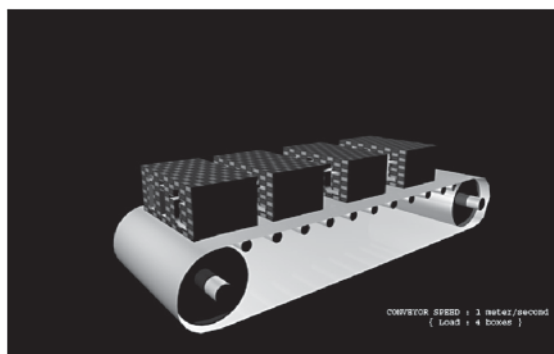
operate at maximum speed. Adjusting speed in these machines is costly and hardware dependent. This is because an increase in the machine size and mechanical parts requires more maintenance and less efficiency. After the discovery of semiconductors and the introduction of semiconductor devices such as diodes and transistors to industry, ASDs have become very popular because of their advantages over traditional control methods. The machine size is smaller and requires less maintenance and hardware.

Using ASDs, the speed of a motor or generator (electric machine) can be controlled and adjusted to any desired speed. Besides adjusting the speed of an electric machine, ASDs can also keep an electric machine speed at a constant level where the load is variable. For example, if the desired speed of the conveyer showed in Fig. 6.1 is 1 m/sec at any time, changing the load will not change the speed (Fig. 6.2).

The variable load can be controlled by just reducing the speed of the electric machine, which means applying less power to the system. As stated above, traditional control methods adjust the speed of the machine to the maximum level, and the machine works



**FIGURE 6.1** Typical conveyer maintaining a constant speed of 1 m/sec with one box as the load.



**FIGURE 6.2** Typical conveyer maintaining a constant speed of 1 m/sec with four boxes as the load.

at that level regardless of the load. In addition, if the load increases, the speed decreases. However, adjustable speed drives can adjust the speed of the machine when the load changes, thereby reducing the applied power to the system.

## 6.1 THE IMPORTANCE OF ELECTRIC MOTOR DRIVES

Electric motors impact almost every aspect of modern living. Refrigerators, vacuum cleaners, air conditioners, fans, computer hard drives, automatic car windows, and multitudes of other appliances and devices all use electric motors to convert electrical energy into useful mechanical energy. In addition to running the commonplace appliances that we use every day, electric motors are also responsible for a very large portion of industrial processes. Electric motors are used at some point in the manufacturing process of nearly every conceivable product that is produced in modern factories. Because of the nearly unlimited number of applications for electric motors, it is not hard to imagine that there are over 700 million motors of various sizes in operation across the world. This enormous number of motors and motor drives has a significant impact on the world because of the amount of power they consume.

The systems that controlled electric motors in the past suffered from very poor performance and were very inefficient and expensive. In recent decades, the demand for greater performance and precision in electric motors, combined with the development of better solid-state electronics and cheap microprocessors has led to the creation of modern ASDs. An ASD is a system that includes an electric motor as well as the system that drives and controls it. Any adjustable speed drive can be viewed as five separate parts: the power supply, the power electronic converter, the electric motor, the controller, and the mechanical load.

The power supply is the source of electric energy for the system. The power supply can provide electric energy in the form of AC or DC at any voltage level. The power electronic converter provides the interface between the power supply and the motor. Because of this interface, nearly any type of power supply can be used with nearly any type of electric motor. The controller is the circuit responsible for controlling the motor output. This is accomplished by manipulating the operation of the power electronic converter to adjust the frequency, voltage, or current sent to the motor. The controller can be relatively simple or as complex as a microprocessor. The electric motor is usually, but not always, a DC motor or an AC induction motor. The mechanical load is the mechanical system that requires the energy from the motor drive. The mechanical load can be the blades of a fan, the compressor of an air conditioner, the rollers in a conveyor belt, or nearly anything that can be driven by the cyclical motion of a rotating shaft.

Electric motor drive technology is constantly evolving and expanding to new applications. More advanced electric motor drives are now replacing older motor drives to gain better performance, efficiency, and precision. Advanced electric motor drives are capable of better precision because they use more sophisticated microprocessor or DSP controllers to monitor and regulate motor output. They also offer better efficiency by using more efficient converter topologies and more efficient electric motors. The more advanced drives of today also offer a performance boost by utilizing superior switching schemes to provide more output power while using lighter motors and more compact electronics.

## 6.2 MOTOR DRIVE PARAMETERS

There are several criteria by which an electric motor drive can be evaluated. The main criteria are efficiency, power factor, harmonic distortion, size, cost, and power density ratio.

Efficiency is one of the most important criteria of modern electric motor drives. Efficiency is simply the mechanical power delivered to the mechanical load divided by the total electrical power consumed by the motor drive. Efficiency is expressed as a percent. For example, if an electric motor drive has an efficiency rating of 75%, exactly three-quarters of the electricity consumed by the motor drive is converted into useful mechanical energy. The remaining one-quarter is lost in the form of heat in the electronics and in the motor. Efficiency is obviously of great importance because of the vast numbers of motor drives throughout the world.

The power factor is technically defined as the cosine of the angle between the voltage and the current supplied to the motor drive. If the AC voltage and current supplied to a motor drive are visualized as sine waves, the power factor quantitatively represents how close the two sine waves are to lining up. If the sine waves of the voltage and current perfectly line up, the power factor is unity. If the sine waves are completely opposite of each other, the power factor is zero. Higher power factors (as close to unity as possible) are desired because they reduce the losses in the electrical power system. Electric utility companies charge an extra fee if the power factor of an industrial load is not above a minimum value. Low power factors cause losses in the power system and cause power quality problems.

Harmonic distortion can occur when a power electronic converter in a motor drive draws a nonsinusoidal current from the power system. There are several other sources of harmonic distortion, including high-intensity discharge lighting, power electronic power supplies, etc. Harmonic distortion can cause serious adverse effects on other equipment running on the same electrical system. Basically, harmonic distortion is a power quality concern that affects the electrical system and other equipment running on the electrical system.

Size and cost are also very critical in evaluating an electric motor drive. The size/weight of a motor drive ultimately determines the feasibility of a motor drive for a particular application. The cost of a motor drive is obviously an important concern in most situations; however, the importance of cost may be overestimated in most cases. In most applications, the cost of the motor/motor drive makes a very small percentage of the money that will be spent on the motor. The vast majority of the expense in most applications is the cost of the energy to run the motor throughout its life. For example, a large industrial motor may cost \$5000 to purchase and install, but will cost \$70,000 in electricity costs to keep it running for its 10-yr life span. This is one major reason that efficiency is so important. An energy-efficient motor drive may cost significantly more than a conventional motor drive, but the capital cost is usually quite small in comparison with the energy costs. In most cases, a more expensive energy-efficient motor drive more than recovers its larger initial cost. This is a very important concept that is often overlooked.

The power/density ratio is important in many applications where space is limited. The power/density ratio is the ratio of power output of a motor drive to the weight or size of the motor drive. Power/density ratio is particularly crucial in vehicular applications, i.e., automotive and aerospace applications, where size and weight are constrained.

Each of the parameters of motor drives described has a different level of importance. The size, cost, and power density ratio of a motor drive determine its suitability for a given application. Each of these has little impact on anyone but the end user of the motor drive. The power factor and the harmonic distortion of a given motor drive are more important properties because they determine the effects on power quality. Power quality issues potentially affect more than just the end user. Motor drive efficiency is the most important property of motor drives in general because efficiency affects everyone. The end user pays for inefficient motor drives in the form of higher electricity costs and society pays for the energy losses in the form of economic waste and ecological damage.

### 6.3 THE IMPACT OF MOTOR EFFICIENCY

The efficiencies of motors and motor drive systems used throughout the world have a large impact on the world in a number of ways. The energy consumed by electric motors accounts for nearly half of all electricity generated in the world today. Because motors make up such a large portion of the world's electrical load, the inefficiency of today's motors results in enormous amounts of wasted energy. The impact of wasted energy in the form of electric motor losses can be broken down into two main categories: economic and ecological. With the constant increase in electricity costs, energy lost due to inefficient motors translates directly to wasted money. Since approximately 75% of the power generated in the United States comes from the burning of fossil fuels, wasted energy due to motor inefficiency needlessly increases the amount of pollution created in the power generation process.

There are currently more than 700 million motors in service worldwide, and approximately 50 million new motors are manufactured every year. These motors come in many different sizes and are used for countless different applications. In the United States (and most other industrialized nations) motors can be classified very roughly into two categories: industrial and residential. Industrial motors are used in applications ranging from mining to manufacturing to the climate control of large commercial buildings. Industrial motors are generally integral horsepower motors, ranging in size from one to several thousand horsepower. Residential motors are used in applications ranging from air conditioning units to refrigerators to dishwashers. Residential motors are generally fractional horsepower motors, ranging in size from a few watts up to about 1 hp. Again, these are very rough classifications that will be used to analyze current motors and the possible benefits of more efficient motors.



The industrial motor load is the largest single category of electrical use in the country. At 679 billion kWh annually (1994 figure), industrial electric motors consume about 23% of all electricity generated in the United States. A very small overall increase in the efficiency of the industrial motor load would lead to enormous savings. For example, if the overall efficiency of industrial motor drives in the United States were increased by merely 0.1%, \$30 million in annual electricity losses would be eliminated. Of course, larger increases in efficiency would translate into much larger savings.

The Office of Industrial Technology of the Department of Energy estimates that industrial motor use could be reduced by as much as 11 to 18% if all cost-effective efficiency technologies and practices were utilized; that translates to annual energy savings of 75 to 122 billion kWh. Note that these efficiency technologies and practices refer to motor efficiency upgrades (using a more efficient motor) as well as system efficiency measures (reducing the mechanical load, using speed controls, better maintenance, etc.). The same study estimates that the initial cost to implement these efficiency technologies and practices would be \$11 to \$17 billion in the form of capital expenditures. The annual savings would amount to between \$3.8 and \$5.8 billion. Thus, in three to four years, the improvements would pay for themselves.

Residential motor load is also a very large portion of the energy used in the United States. Approximately 445 billion kWh are consumed annually by the small motors used in residential applications. This is roughly one-quarter of all energy used by the residential sector. Like the industrial sector, the residential sector could also greatly benefit from more efficient motor drives. However, it is even more feasible to introduce more efficient motor drives to residential applications because the life spans of household appliances and gadgets are generally shorter than the life spans of large industrial machines. Thus there are more opportunities to replace inefficient motors. In addition, the price difference between highly efficient and typical motor drives is smaller at the residential level than it is at the industrial level. While a high-efficiency refrigerator may cost \$20 to \$50 more than a similar unit with lower efficiency, a large industrial high-efficiency motor drive may cost hundreds or even thousands more

than less efficient motor drives. Therefore there are more opportunities to increase the efficiency of motor drives used in residential applications.

Power consumption and loss translates directly into fuel used in power generation. The slight increases in efficiency that could save customers millions of dollars a year in electricity could also conserve dwindling fossil fuel supplies and keep unnecessary pollutants out of the atmosphere. In the year 2000, 23.4 billion tons of CO<sub>2</sub> were released into the atmosphere as a result of worldwide power production. Since the electricity used by motors and motor drives accounts for approximately half of the world's power demand, it is logical to conclude that approximately 11 billion tons of CO<sub>2</sub> result from the use of all motors annually. To put this number in context, the entire Amazon rainforest absorbs about 2 billion tons of CO<sub>2</sub> annually. If all motor drives worldwide experienced an efficiency increase of 0.1%, approximately 10 million tons of CO<sub>2</sub> would not be released into the atmosphere. This is the amount of CO<sub>2</sub> absorbed by approximately 1 million hectares of temperate forest (which is one-tenth of all the forest land in Europe). When considering the direct but often overlooked correlation between energy use and pollution, the case for more efficient motor drives becomes much stronger. Table 6.1 lists potential global effects of motor drive efficiency improvements.

The number of electric motors, and hence the number of motor drives, is increasing. Fortunately, technological advances

**TABLE 6.1** Global Effects of Motor Drive Efficiency Improvements

| Global increase<br>in motor<br>drive efficiency | Approximate cost<br>of electricity saved<br>(based on average<br>5¢ kWh) | Approximate amount<br>of CO <sub>2</sub> kept out<br>of atmosphere |
|-------------------------------------------------|--------------------------------------------------------------------------|--------------------------------------------------------------------|
| 0.1%                                            | \$600 million                                                            | 10 million metric tons                                             |
| 0.5%                                            | \$3 billion                                                              | 50 million metric tons                                             |
| 1.0%                                            | \$6 billion                                                              | 100 million metric tons                                            |

in power electronics, microprocessors, and electric motors are resulting in advanced motor drives that boost performance while increasing efficiency. The motor drive market is expected to grow from \$12.5 billion in 2000 to \$19 billion by 2005. This large market growth is responsible for making advanced motor drives more profitable and thus more common. The widespread use of high-efficiency, advanced motor drives creates the possibilities of reducing energy costs for end users, reducing the consumption of fossil fuels for energy production, and decreasing the amount of harmful emissions released into the atmosphere. The world has much to gain by researching advanced motor drives.

## 6.4 CURRENT MOTOR TECHNOLOGY

In today's modern world, electronics are everywhere, from handheld computers to air conditioners to projection TVs. However, even now over half of all power consumption in the United States can be accounted for by motors. These motors can vary from a simple blender and fan motor to an industrial motor used for assembly lines in automobile factories. When you consider the mass power that the United States consumes in a year, it becomes apparent that if one can make these motors run even a couple tenths of a percent more efficiently, it can make a huge difference in power savings. The purpose of this section is to first explain current motor technology and where efficiency efforts stand to date. The second purpose is to document future design innovations and their effect on overall efficiency.

Electric motors convert electrical energy into useful mechanical energy. This energy can then be used to drive household appliances, e.g., fans, compressors, etc.; but even in home applications, not all motors are alike. Different types have varying characteristics (and thus different efficiencies), making them suitable for certain situations but not for others. Single-speed induction motors are presently being used for most residential applications ranging from portable fans to compressors commonly found in refrigerators. These include both single- and three-phase squirrel-cage and shaded-pole induction motors. There is a noteworthy dissimilarity and a rather wide range of

efficiency between these single-speed induction motors. Shaded-pole motors tend to be lower on the efficiency scale. It is also worth mentioning that in general motor efficiency comes at the price of horsepower, and for this reason smaller motors are generally less efficient.

Universal AC/DC motors are commonly used for sporadic applications where high speed is needed. Examples of this would be drills, food processors, and vacuums. These are the “brush motors” (named for the set of brushes that constantly change voltage, thus keeping the motor spinning in an attempt to align polarity). The main problem with these types is significant losses associated with the windings’ wear and tear on the brushes (most small motors fail due to worn brushes).

Induction motors are found in refrigerators and air conditioners, but in many cases also in washing machines. It is in this area that a greater efficiency would yield huge returns in the long run.

## 6.5 ADVANTAGES OF VARIABLE-SPEED MOTORS

Most motors are designed to operate at a constant speed and provide a constant output. While in many cases this may be more than adequate, it is not in all. Two-speed induction motors can improve efficiency for refrigerators, air conditioners, and blowers. Although in theory this can be done with any induction motor application, a greater value is obtained with appliances that run frequently. With a two-speed mode of operation, long time periods that would normally use full power can be replaced by long periods of substantially less power with short periods when full power may be needed. Currently, residential central air conditioners, blowers (furnaces), and clothes washers take advantage of this technology since small changes in speed can drastically cut down on power usage (power consumption is approximately proportional to the cube root of shaft speed, e.g., a shaft reduction of 10% corresponds to at 27% reduction of power).

There are many ways to control the shaft speed of a motor. The most common way is via throttling devices such as valves and inlet vanes. However, this type of control is comparable to driving a car at a high speed and controlling the speed by using the brake. Another

way is by using ASDs. This type of drive controls the speed by regulating the voltage, current, and/or frequency sent to the motor until the approximate load speed is obtained. Several types of ASDs are available, each with its own characteristics and practical applications. Even in these devices, there are many different kinds. Pulse width modulation (PWM) ASDs work by chopping pulses of varying widths to create the desired output voltage. They do this by using computer software which in turn is controlled by complex algorithms monitoring timing, duration, and frequency. This type of ASD has a rather high power factor, good response time, as well as low harmonic distortion. They also have the capability to control many different motors from the same system. Their downfall is higher heat dissipation and a limited data cable length from the control to the motor.

Voltage source inverter (VSI) ASDs can also control many motors from a single drive and have the advantage of simple circuitry (an advantage that does not exist in PWM ASDs). They normally have a capacitor before the inverter to help store energy and keep the voltage stable. Their control ranges from about 10 to 200% of rated motor speed; however, below 10% it breaks down and becomes very inefficient.

The last common type of ASD is the current source inverter (CSI). It uses the inductive characteristics of the motor to stabilize DC as it reaches the inverter. Because this induction has to be rather large, this type of drive can only be used in medium to large motors. Advantages include short-circuit protection, quiet operation, and high efficiency at a wide range of speeds (normally above 50%). However, disadvantages include the inability to test the drive while not connected to a motor and complexity in connecting multiple motors to a single drive. [Table 6.2](#) summarizes the characteristics of these four types of drives. Although many of these applications are beyond utilization for the small-scale motors being analyzed, it is mentioned to point out the potential energy saving for similar systems on an achievable smaller scale.

## 6.6 GOVERNMENT REGULATION

Recently, the federal government has made great attempts to strive for higher efficiencies in consumer goods. These attempts include

TABLE 6.2 Characteristics of Different Drives

|                            | Pulse width modulation | Voltage source inverter | Current source inverter |
|----------------------------|------------------------|-------------------------|-------------------------|
| Ease in retrofitting       | Yes                    | Yes                     | No                      |
| Soft start                 | Yes                    | Yes                     | Yes                     |
| Regeneration               | Option <sup>a</sup>    | Option <sup>a</sup>     | Inherent                |
| Motor heating              | High                   | Low                     | Low                     |
| Motor noise                | High                   | Low                     | Low                     |
| Partial loading            | Yes                    | Yes                     | Unstable                |
| Low-speed operation        | Smooth                 | No                      | No                      |
| Low-speed torque pulsation | No                     | Yes                     | Yes                     |
| Frequency above 60 Hz      | Yes                    | Yes                     | No                      |
| Open-circuit protection    | Inherent               | Inherent                | Required <sup>b</sup>   |
| Short-circuit protection   | Required <sup>b</sup>  | Required <sup>b</sup>   | Inherent                |
| Overload protection        | Required <sup>b</sup>  | Required <sup>b</sup>   | Inherent                |
| Multimotor drive           | Yes                    | Yes                     | Option <sup>a</sup>     |
| Controller and logic       | Complex                | Simple                  | Semicomplex             |
| 60-Hz power factor         | High                   | Poor                    | Poor                    |
| 60-Hz harmonics            | Low                    | High                    | High                    |
| Motor harmonics            | High                   | Moderate                | Moderate                |
| Voltage stresses on motor  | Yes                    | No                      | Yes                     |
| DC filter size             | Small                  | Large                   | Large                   |
| Inverter noise             | High                   | Medium                  | Medium                  |
| Transistor/GTO technology  | Yes                    | Yes                     | No                      |
| Inverter switches          | High frequency         | Low frequency           | Low frequency           |
| Size and weight            | Small                  | Medium                  | Small                   |

<sup>a</sup> Feature is available at extra cost.

<sup>b</sup> Feature must be provided by the system design.

Source: Courtesy Pacific Gas and Electric Co.

minimum efficiencies that appliances must achieve. This has been done by to the passing of the National Appliance Energy Conservation Act (NAECA) in 1990. Since the passing of this act, appliance manufacturers have made great improvements, especially in refrigerators and freezers. It is for this reason that replacing an older refrigerator or freezer can lower the household energy usage by a significant amount. It has also been made law that all new major appliances show their efficiencies where the consumer can easily see them when making their purchase decision. This is done to try to alert the consumer of the importance of energy savings and its effect on goods. It also serves to show the consumer that they cannot ignore the fact that the energy cost of running an appliance can certainly outweigh its cost.

We now review the few cases where motor improvements create huge savings in the long run. A case for appliance replacement is furnace fans. Although newer models are much more efficient, most residents are using older models. These models can use quite a lot of energy. Right now most forced air systems and air conditioners use multiple-speed, shaded-pole, or permanent-split capacitor induction motors. The efficiency of these is in the 50–60% range when a single speed is selected to match the rest of the system. In these cases, there are not one or two but three options that may be used to improve efficiency. They include a high-efficiency motor, an ECM (electronically commutated permanent magnet) motor, and a variable-speed ECM motor. These can add anywhere from \$15 to \$75 to the retail cost of the system; however, they quickly pay for themselves in energy savings and will continue to lower energy costs. The case is very similar for heat pump blowers as well.

Air conditioners have also been through many changes since efficiency regulation. Their levels have risen from 10.5 to 11.5 only in the last decade. However, traditional motor improvement is coming to 2–3% of its practical limit (in the case of the compressor motor). This leaves very little room for traditional improvements; for example, if a compressor with 80% efficiency is being driven by a 90% efficient motor, the new rating would be only 11.8, a small difference considering the work involved in achieving the compressor and motor efficiencies. This brick wall is mainly due to the fact that air conditioners primarily operate at

a single speed, cycling on and off to meet the current load required (some also control output with valves and dampers; at times these may be even less efficient). The solution is a variable-speed motor that would operate at highly variable loads by matching the speed to the load. This would save energy and extend the life of the motor by allowing it to operate less often at full throttle. Because applying this strategy would involve more than just improving

**TABLE 6.3** Effects of Efficient Motor Options for Indoor Blowers

| Motor                          | Efficient motor option | Energy savings, % | Energy savings, \$/yr | Additional retail cost, \$ | Simple payback, yr |
|--------------------------------|------------------------|-------------------|-----------------------|----------------------------|--------------------|
| Central A/C blower             | High-efficiency PSC    | 14                | 4.50                  | 15                         | 3                  |
|                                | ECM                    | 25                | 8.00                  | 40                         | 5                  |
|                                | Variable-speed ECM     | 75                | 24.00                 | 75 <sup>a</sup>            | 3                  |
| Heat pump blower               | High-efficiency PSC    | 14                | 11.20                 | 15                         | 1                  |
|                                | ECM                    | 25                | 20.00                 | 40                         | 2                  |
|                                | Variable-speed ECM     | 75                | 60.00                 | 75 <sup>a</sup>            | 1                  |
| Furnace blower                 | High-efficiency PSC    | 14                | 6.70                  | 15                         | 2                  |
|                                | ECM                    | 25                | 12.00                 | 40                         | 3                  |
|                                | Variable-speed ECM     | 75                | 36.00                 | 175 <sup>b</sup>           | 5                  |
| Central A/C and furnace blower | High-efficiency PSC    | 14                | 11.20                 | 15                         | 1                  |
|                                | ECM                    | 25                | 20.00                 | 40                         | 2                  |
|                                | Variable-speed ECM     | 75                | 60.00                 | 175 <sup>b</sup>           | 2                  |

<sup>a</sup> Cost of variable-speed blower only.

<sup>b</sup> Includes incremental cost of \$100 for capacity modulation in the furnace.  
*Source:* homeenergy.org.



efficiency in an already designed air conditioner—in fact, in most cases it involves redesigning the entire unit as a whole—manufacturers are very reluctant to take this approach.

Residential refrigerators and freezers can have up to three motors (excluding ice makers and defrost timers); the largest drives the refrigerant compressor. In frost-free units (the most common), two additional motor units drive fans that circulate air over the condenser and evaporator. The compressor is normally an AC single-phase, two-pole induction motor. In order to comply with a dramatically reduced allowable refrigerator and freezer energy consumption by

**TABLE 6.4** Potential for Residential Energy Savings Through Increased Motor Efficiency

| Application                       | Total<br>national<br>motor energy<br>use, 10 <sup>9</sup><br>kWh/yr | Current<br>motor<br>efficiency<br>savings,<br>% | Practical<br>efficiency, <sup>a,b</sup><br>% | Potential<br>energy |                     | Typical<br>payback, <sup>b</sup><br>yr |
|-----------------------------------|---------------------------------------------------------------------|-------------------------------------------------|----------------------------------------------|---------------------|---------------------|----------------------------------------|
|                                   |                                                                     |                                                 |                                              | %                   | 10 <sup>9</sup> kWh |                                        |
| Refrigerators and freezers        |                                                                     |                                                 |                                              |                     |                     |                                        |
| Compressor                        | 101                                                                 | 80                                              | 82–84                                        | 4                   | 4.0                 | 14                                     |
| Condenser fan                     | 6                                                                   | 15                                              | 65                                           | 77                  | 4.6                 | 6                                      |
| Evaporator fan <sup>c</sup>       | 6                                                                   | 15                                              | 65                                           | 128                 | 7.7                 | 4                                      |
| Central A/C and heat              |                                                                     |                                                 |                                              |                     |                     |                                        |
| Pump compressor                   | 159                                                                 | 87                                              | 90                                           | 3                   | 5.5                 | 16                                     |
| Outside unit fan                  | 21                                                                  | 50                                              | 70                                           | 29                  | 6.1                 | 6                                      |
| Room A/C compressor               | 25                                                                  | 87                                              | 90                                           | 3                   | 0.8                 | 13                                     |
| Indoor A/C and<br>heating blowers | 61                                                                  | 60                                              | 80                                           | 25                  | 15.3                | 3                                      |
| Clothes washer<br>motor           | 10                                                                  | 65                                              | 75                                           | 13                  | 1.3                 | 10                                     |

<sup>a</sup> Based on upgrading installed motor base to maximum practical efficiency levels.

<sup>b</sup> Assuming average electric rate of \$0.08/kWh.

<sup>c</sup> Includes reduction in compressor load.

*Source:* Opportunities for Energy Savings in the Residential and Commercial Sectors with High Efficiency Electric Motors, U.S. Department of Energy.

the federal government in 2001 and even more reductions foreseeable in the near future, manufacturers are now considering ECMs. These would adjust to load conditions either at a constant speed or at a variable speed. Either of these options would be a great improvement over current practices in which the compressor motor runs at full speed until the desired temperature is met, then cycles on and off between full speed and off.

It is estimated that replacing both the condenser motor and fan motor would increase the retail price by only \$75; but the consumer would see the improvement pay for itself in a few years. Table 6.3 shows the efficient motor options for indoor blowers. Table 6.4 shows the potential for savings by increased motor efficiency. And Table 6.5 displays the potential for saving by variable speed motors.

**TABLE 6.5** Potential for Residential Energy Savings Through Variable-Speed Motors

| Application                                       | Total national motor energy use, 10 <sup>9</sup> kWh/yr | Current motor efficiency, % | Practical efficiency, <sup>a</sup> % | Energy savings |                     | Typical payback, <sup>b</sup> yr |
|---------------------------------------------------|---------------------------------------------------------|-----------------------------|--------------------------------------|----------------|---------------------|----------------------------------|
|                                                   |                                                         |                             |                                      | %              | 10 <sup>9</sup> kWh |                                  |
| Refrigerator/freezer compressor                   | 101                                                     | 80                          | 88                                   | 20             | 20.2                | 8                                |
| Central A/C and heat pump compressor <sup>c</sup> | 159                                                     | 87                          | 90                                   | 35             | 55.7                | 15–25                            |
| Room A/C compressor                               | 25                                                      | 87                          | 90                                   | 10             | 2.5                 | 20+                              |
| Indoor heating and A/C blowers                    | 61                                                      | 60                          | 80                                   | 75             | 45.9                | 2–3                              |

<sup>a</sup> Based on upgrading installed motor base to maximum practical efficiency levels.

<sup>b</sup> Assuming average electric rate of \$0.08/kWh.

<sup>c</sup> Using a two-speed induction motor. (Somewhat higher energy savings are possible with a continuously variable-speed motor, but the payback period is longer.)

*Source:* Opportunities for Energy Savings in the Residential and Commercial Sectors with High Efficiency Electric Motors. U.S. Department of Energy.

## **6.7 ADJUSTABLE-SPEED DRIVE APPLICATIONS**

Adjustable-speed drives can be used in every environment where variable speed and torque are needed. ASDs are currently used in elevators, water and wastewater pumps, boiler fans, HVAC systems, wind turbines where speed of wind is not constant, hydroelectric plants where speed of water is not constant, and the automobile industry. Some of these applications will be discussed in detail below.

Over the last few years there has been an increase in demand for electrical energy that has been made by wind energy, an alternative energy source. Wind speed is variable and applies variable speeds to the generator at the turbine, which creates different frequency levels. To increase productivity and get 60-Hz frequency at the output, adjustable-speed drives can be used in wind turbines. In advanced systems, wind is converted to electrical energy via an AC generator with variable frequency and voltage levels. By using a converter, this AC is converted to DC; then, using a DC link line, this DC is transmitted to a DC/AC inverter. The AC utility line has fixed voltage and frequency with better power quality. Illinois, Texas, and Arizona in the United States as well as Denmark and others use wind energy. Other countries are sure to follow.

As with wind energy, water flow also has variable speed. This again creates variable voltage, frequency, and a poor power factor. By using ASDs, these problems can be fixed and the AC utility line can have fixed values. In such advanced systems, water flow is converted into electrical energy via an AC generator with variable frequency and voltage levels. By using a converter, this AC is converted to DC; then, using a DC link line, this DC is transmitted to an inverter connected to the AC utility line, which has fixed voltage and frequency with better power quality. This increases quality and efficiency. Hydroelectric power plants are one of the oldest and biggest electrical energy creation systems.

Centrifugal pump and fan applications are among of the most common areas for ASDs. Gas or liquid flow can be regulated using ASDs. Adjustable-speed drives can reduce maintenance costs and increase the efficiency of pumps to almost the best efficiency point.

In Table 6.6, the relationships among the speed of a pump, liquid flow, and horsepower needs are shown. As seen in the table, increments in the flow and speed will greatly decrease power requirements. If the speed of the pump decreases by 50%, the power requirements will go down to 13%. This shows that ASDs can be very efficient and save money.

In conclusion, ASDs and their applications have been rapidly growing over the last few years. There are many applications, like fans, compressors, pumps, automobile industry applications, and many other motor areas, where variable-speed drives are desirable and can be readily found. There are some downsides to ASDs, such as harmonics, voltage notching, and complexity of design and cost, but these can be fixed using harmonic filters, voltage regulators, and switching control mechanisms. Use of ASDs will increase the efficiency of machinery, lower maintenance costs, and reduce machine size. Faster-switching semiconductor devices and a decrease in semiconductor prices make this field very popular for engineers and the industry. Available ASDs can be purchased as AC or DC drives. AC drives can adjust the frequency and voltage to change the speed of the electric machine. Creating a voltage and frequency ratio constant will create a constant torque. These drives are newer and simpler compared to the DC drives, but they are not as efficient. AC machines need less maintenance than DC machines and motor speed can reach almost four times more than DC machines. Another advantage of using vector-controlled AC machines is that fast-changing load applications can be used. DC

**TABLE 6.6** Flow–Speed–Power Relationships of Typical Pumps

| Flow, % | Speed, % | Horsepower, % |
|---------|----------|---------------|
| 30      | 30       | 3             |
| 50      | 50       | 13            |
| 70      | 70       | 34            |
| 80      | 80       | 51            |
| 90      | 90       | 73            |
| 100     | 100      | 100           |

drives need converters to convert AC utility voltage into DC voltage, and by changing this the voltage speed of the machine can be altered. DC machines require better maintenance and therefore its environment needs to be clean and dry. Adjustable-speed drives are one of the newest and fastest growing technologies in electric machines, and their future will certainly be dynamic.

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